Heavy Ion Fusion Sciences Virtual National Laboratory

Issue Number 3, October 2009

HIFS News

NDCX-II project is underway

Earlier this year, the Department of Energy Office of Fusion Energy Sciences approved the HIFS-VNL's NDCX-II project (a second-generation Neutralized Drift Compression eXperiment). Supported by $11 M of stimulus funding from the American Recovery and Reinvestment Act, construction at LBNL commenced in July, with completion anticipated in March of 2012. The project is a collaborative effort of scientists and engineers at all three VNL labs.

As with the existing NDCX-I, the new machine will produce short ion pulses using the technique of neutralized drift compression. A head-to-tail velocity gradient is imparted to the beam, which then shortens as it drifts in a neutralizing plasma that suppresses space-charge forces. NDCX-II will make extensive use of induction cells and other hardware from the decommissioned ATA facility at LLNL. Figure (1) shows the layout of the facility, to be sited in LBNL's Building 58 alongside the existing NDCX-I apparatus.

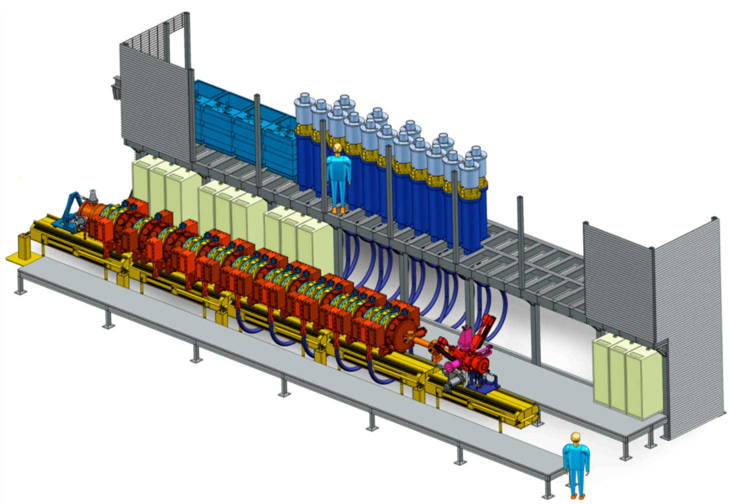

Figure 1. Computer-aided-design rendering of NDCX-II. The ion source and injector are at the left; voltage sources (blue) reside on a mezzanine; the induction cells are in yellow-red; and the drift-compression line and target chamber are at the right.

This second-generation facility represents a significant upgrade from the existing NDCX-I. It will be extensible and reconfigurable; in the configuration that has received the most emphasis, each NDCX-II pulse will deliver 30 nC of ions at 3 MeV into a mm-scale spot onto a thin-foil target. Pulse compression to ~ 1 ns occurs in the accelerator as well as in the drift compression line; the beam is manipulated using suitably tailored voltage waveforms in the accelerating gaps.

NDCX-II employs novel beam dynamics. To use the 200 kV Blumlein power supplies from ATA (blue cylinders in

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Enhancing the self-focusing of an ion beam pulse in a plasma with a solenoidal magnetic field

The enhancement of the self-focusing effect of an ion beam propagation through a plasma with an applied solenoidal field was demonstrated recently and reported in [1]. The effects of the enhanced self-focusing can be of particular importance for the presently operating Neutralized Drift Compression Experiment NDCX-I [2] and its future upgrade NDCX-II [3].

Neutralization and focusing of charged particle beam pulses by a background plasma form the basis for a wide range of applications to high energy accelerators and colliders, ion-beam-driven high energy density physics, heavy ion fusion, and astrophysics. Even for the simple case where an ion beam pulse propagates through a dense neutralizing background plasma without an applied magnetic field, its space-charge is typically better neutralized than its current. As a result, a net focusing (self-pinching) force is produced due to the self-magnetic field. The effects of self-pinching become most pronounced when the beam radius r_b is small compared to the collisionless plasma electron skin depth, $r_b<c/\omega_{pe}$, where ω_{pe} is the electron plasma frequency and c is the speed of light. In such a case, it was recently demonstrated [1] that the self-focusing force can be significantly enhanced if a moderately weak solenoidal magnetic field satisfying $\omega_{ce}>>\omega_{pe}\cdot V_b/c$ is applied along the beam propagation direction, where ω_{ce} is the electron cyclotron frequency associated with the applied magnetic field and V_b is the beam velocity.

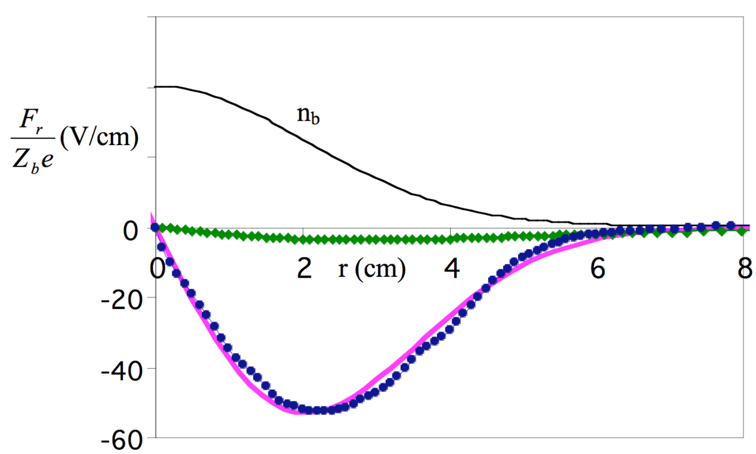

Figure 3. Radial dependence of the normalized focusing force at the beam center for: (green) no applied field; (blue) applied B_0=300 G from numerical simulations; (pink) applied B_0=300 G from analytical formula. The black curve corresponds to the radial beam density profile.

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This work was supported by the Director, Office of Science, Office of Fusion Energy Sciences, of the U.S. Department of Energy prepared by LBNL under Contract No. DE-AC02-05CH11231, by LLNL under Contract DE-AC52-07NA27344, and by Princeton Plasma Physics Laboratory under contract No. DE-AC02-76CH-O3073.

LBNL-PUB-844-02-2008

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the figure), the pulse duration must first be reduced to less than 70 ns. This shortening is accomplished in an initial stage of non-neutral drift compression, downstream of the injector and the first few induction cells. The compression is sufficiently rapid that only seven long-pulse custom power supplies are needed, with Blumleins powering the rest of the acceleration.

Extensive simulation studies have enabled an attractive physics design [1-3]; these employ both a new 1-D code (ASP) and the VNL's workhorse 2-D/3-D code Warp. Snapshots from a simulation movie (available online [4]) appear in Fig. 2.

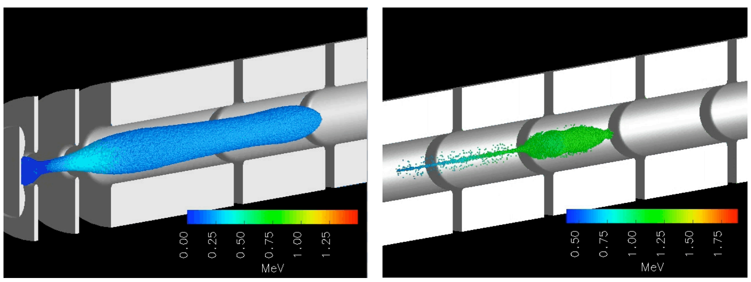

Figure 2. Images from a 3-D Warp simulation of NDCX-II, showing the beam as it exits the injector and partway through the machine

Studies [5] on a dedicated test stand are quantifying the performance of the ATA hardware and of improved solenoids that will provide transverse beam confinement (ions require much stronger fields than the electrons accelerated by ATA).

Applications of this facility will include studies of the basic physics of Warm Dense Matter using uniform volumetric ion heating; ion energy coupling into an ablating plasma using beams with time-varying kinetic energy; space-charge-dominated ion beam dynamics; and beam focusing and pulse compression in the presence of neutralizing plasma. Much of this research will contribute directly toward the collaboration's ultimate goal of electric power production via heavy-ion beam-driven inertial confinement fusion.

For more information, see a recent article in the Berkeley Lab News [6], and our progress report to DOE [7].

- Alex Friedman

[1] A. Friedman *et al*., Nucl. Instr. and Meth. A **606**, 6 (2009).

[2] W. M. Sharp *et al*., Proc. 2009 Particle Accel. Conf., http://hifweb.lbl.gov/public/papers/Sharp-PAC09ms.pdf

[3] A. Friedman *et al*., Proc. 2009 Int'l. Comput. Accel. Conf., http://hifweb.lbl.gov/public/ICAP09/TH1IOpk04.pdf

[4] http://hifweb.lbl.gov/public/movies/ICAP09

[5] W. L. Waldron *et al.,* Fusion Sci. Technol. **56**, 452 (2009).

[6] http://newscenter.lbl.gov/feature-stories/2009/10/14/warm-dense-matter

[7] NDCX-II Quarterly Progress Report to DOE/OFES for FY09Q4, http://hifweb.lbl.gov/public/papers/NDCX-II_Quarterly_Report_091008.pdf

Enhanced Self-Focusing continued from page 1

A significant increase in the self-focusing force in the presence of a weak applied magnetic field has been observed in electromagnetic particle-in-cell simulations performed using the 2D cylindrical version of the LSP code, and confirmed by an analytical model. As an illustrative example, we consider a Gaussian ion beam pulse with an effective beam radius $r_b=0.55c/\omega_{pe}$, beam pulse half-length $l_b=1.875c/\omega_{pe}$ (beam pulse duration $\tau_b=75/\omega_{pe}$), propagating with velocity $V_b=0.05c$ through a background plasma with density $n_p=10^{10}$ cm^{-3}. The results from simulations and our analytical formula are shown in Fig. 3. A significant enhancement of the radial component of the Lorentz force due to an applied magnetic field of B_0=300 G ($\omega_{ce}=18.7\omega_{pe}\cdot V_b/c$) is evident from the results of the numerical simulations and are found to be in good agreement with the analytical predictions (pink curve in Fig. 3).

The effects of the enhanced self-focusing can be of particular importance for the presently operating Neutralized Drift Compression Experiment NDCX-I [2] and its future upgrade NDCX-II [3], where the ion beam pulse is first compressed ballistically as it propagates through a long drift section filled with a background plasma, and is then focused on the target by a strong (several Tesla) final focus solenoid. We note that for the parameters characteristic of the NDCX-I and NDCX-II experiments the beam radius is small compared to the electron skin depth. The threshold magnetic field in the inequality $\omega_{ce}>>\omega_{pe}\cdot V_b/c$ corresponds to a relatively weak magnetic field of the order of 5 G (for NDCX-I) and 50 G (for NDCX-II). The magnetic fringe fields of the final-focus solenoid, which is significantly above these values, can penetrate deep into the drift section, thus providing conditions for the enhanced self-focusing. Finally, we showed in [1] that the plasma-induced collective focusing effect in a several hundred gauss magnetic field inside the long drift section can become comparable to the focusing effect of a strong final focus solenoid for the design parameters characteristic of NDCX-II.

- Mikhail Dorf

[1] M. Dorf, I. Kaganovich, E. Startsev and R. Davidson, Phys. Rev. Lett. **103**, 075003 (2009).

[2] P.A. Seidl *et al*., Nucl. Instr. and Meth. A **606**, 75 (2009).

[3] A. Friedman, this issue.

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LBNL-PUB-844-02-2008